Synoptic of the Research Activity (Updated version, Oct. 2007)

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The research activity includes a thematic change in 1979 (from Computer Graphics to Robotics). It can roughly been divided into five main periods : "Computer Graphics and CAD" (1974-78), "Robot programming and simulation" (1979-85), "Motion Planning & CAD Robotics" (1986-95), "Motion autonomy & Dynamic Simulation" (1996-02), "Geometry and probability for motion and action" (since mid-2002). The last period represents a deep methodological and thematics change with the past research. This research activity covers three important aspects : theoretical developments, experimental validations using complex experimental setups (various robots, sensors, and automatic vehicles), and valorization (start-ups, technological transfers, and various industrial partnerships).

Period 1 : Computer Graphics & CAD.
The work achieved during this first period was focused onto the study of graphical representations and of graphic interactions. It has mainly lead to the achievement of a Doctorate Thesis (French PhD) on graphical representations [14], and to some original results on the automatic interpretation of 2D hand drawings [226] and on the graphical visualization of 3D objects [289] ; it has also given rise to the implementation of two graphical softwares (*GRIGRI* [292, 296] and *LISP3D* [287]), which have widely been used during several years at the IMAG Laboratory in Grenoble and at the CAD center of the MICADO company. The software *LISP3D* has been developed during the period of transition between the fields of Computer Graphics and of Robotics, and it included some new constructions for representing poly-articulated systems and robots (this characteristic was pretty original at this period where CAD-Robotics was just starting).

Period 2 : Robot Programming & Simulation.
The work during the second period was centered onto the study of the problems involved in *robot programming and in robot simulation* (in particular geometrical models and algorithms). During this period, I have actively participated to the creation of the ITMI company (1982) and of the GETRIS Images company (1985), and I have taken the leadership of the AI & Robotics research team of the LIFIA Laboratory (this research team was previously leaded by Jean-Claude Latombe until 1984). Two important scientific results have been obtained during this period : (1) *the development and the commercialization by the ITMI company of the LM system for robot programming* (my personal contribution being mainly centered onto the CAD and simulation functions) [219, 31, 247, 59, 58] ; (2) *the principle of topologic/geometric analysis of quasi-static stability properties* for automatic grasping in Robotics. This approach for automated grasping, initially published in [224] and in [30], has been used as the basements for several works in our research team (in particular the PhD thesis of J. Pertin-Troccaz in 1985 and our pioneer work in the field of dexterous grasping) ; it has also inspired some works at the international level (for instance, T. Lozano-Perez from MIT has re-used the concept of "P-Convexity" and some contemporary developments at the university of Karlsruhe relies on this principle). Later on, this approach for automatic grasping has been extended in order to integrate sensing data and more complete motion planning techniques [52].

Period 3 : Motion Planning & CAD-Robotics.
The work done during the third period was mainly focused onto the concepts of *Motion Planning and of Geometric Reasoning* . This work is representative of my second Doctorate Thesis (French "Thèse d'Etat") [13], which has been finalized during my stay at MIT in the summer 1989 under the supervision of Jean-Claude Latombe. This work, which includes the contributions of several PhD students having worked under my supervision, has given a strong "Automatic Robot Programming" identity to our research team (the main competitor on this topic was the team of Thomas Lozano-Perez at MIT AI Lab). The approach consists in formalizing the characteristics of the various motions to be planned (free space motions, grasping & stability, manipulation & uncertainty), and in trying to develop the most appropriate models and algorithms. This work has given rise to the implementation of a prototype system (the *SHARP* system [248]) ; it has also given rise, in conjunction with the work done by Emmanuel Mazer, to a technological transfer (the *ACT system* [200], commercialized by the *Aleph Technologies* company, and developed in collaboration with Bernard Faverjon from Inria Sophia-Antipolis). From the conceptual point of view, the most original part of this work relies in fact that we have developed a formalism and various algorithms for *explicitly taken into account the additional constraints coming from the physical world*, while trying to master the intrinsic algorithmic complexity of these problems (the algorithmic complexity being already of an exponential nature before considering these additional constraints) : uncertainty [54, 51], vision perception [24], wheel/ground interactions [55, 170, 161]. Our results in the field of CAD-Robotics have lead to the creation of the *Aleph Technology* company (1989), and our original approach for modeling the wheel-ground interactions in mobile robotics is at the origin of more recent developments at the SimTech Institute in Singapore.

Period 4 : Motion autonomy & Dynamic simulation.
This research period put the emphasis onto two important concepts for the development of Robotics : *Motion Autonomy and Dynamic Simulation*. Most of the work done in the field of Motion Autonomy has been performed in the context of the Automated Road application, by considering some new and important dimensions of the movement : kinematics, dynamics, and reactivity with respect to hazards inherent to the real world. Our approach, which has already been

tested on several real vehicles, consists in both developing the models and algorithms required for dealing with the above-mentioned constraints [191, 135, 236, 230], and in integrating these methods into a control architecture combining a decisional layer and a reactive layer using the new concept of “Sensor-Based Maneuver” [50, 18]. This work has allows us to skip from traditional “academic geometric planners” to *motion planners having the capability to generate solutions which are executable on real vehicles* : e.g. planning continuous curvature paths with bounded derivatives in order to take into account the physical steering constraints of a car [135], the concept of “time-state” and more recently the concept of “Velocity-Obstacle” for taking into account the dynamic characteristics of the car and of the environment [191, 230], a real-time incremental planning paradigm for controlling the parking maneuvers of an autonomous vehicle [148]. This work has also given rise to numerous public demonstrations (exhibitions, TV shows, official events), and to two patents : a first one in 1997 on “car parking assistance” (with Igor Paromtchik) which has finally not been accepted because of an anterior publication of the work (it should be noticed that Toyota has commercialized in 2004 a product which seems to be based on the same philosophy) ; a second one on the use of the concept of “V-Obstacle for collision avoidance in a dynamic environment”(with Frederic Large, Sepanta Sekhavat, and Zvi Shiller).

During this period, we have also initiated a pioneer work on the new concept of *Dynamic Simulation for Robotics* (it was 10 years ago, at a time where almost nothing was done on this topic). This work was motivated by the fact that classical geometric models are not appropriate for dealing with some physical constraints of robotics tasks (e.g. wheel-ground interactions for off-road vehicles, object-finger interactions in dexterous manipulation of non necessarily rigid objects). Later on, our approach has been extended in order to be able to address simulation problems for medical applications. This work has mainly given rise to the development of models and algorithms for processing in an integrated way movements, deformations, and physical interactions (e.g. collisions and haptic interaction) [153, 19, 47, 43]. Two systems exhibiting such characteristics have been developed (*Robotϕ* and *AlaDyn3D*), patented at APP (with Ammar Joukhadar and Anton Deguet), and used at various levels (internal use, Web, customized versions at the Orthopedic Institute of Bologna and at the Getris company). From the conceptual point of view, the main originality of our work relies at two layers : (1) the development of *efficient geometric algorithms* for processing 3D interactions (e.g. efficient collision detection between deformable objects [131], determination of fictive interpenetrations and of collision forces [122]*(finalist best paper award atICARCV'00)* [49]), and (2) the development of *interactive “reality-based” simulation techniques* (identification of the model parameters from measures done on real bodies [140, 126], efficient models for simulating biological tissues using Mass-Spring Networks or Explicit Finite Elements [125, 126, 98] or using a new type of model — the *LEM* model (best paper at PUG'00) and the *VDM* model recently used in a knee arthroscopy application [46]— based on the Pascal principle and on the volume conservation principle [112, 231], haptic interaction with complex deformable bodies and simulation of some associated complex phenomena such as cutting or tearing [113, 111, 231, 98]. This approach has been used for implementing various medical simulators :“Liver surgery simulator” developed in cooperation with the Epidaure project at Inria Sophia-Antipolis and IRCAD institute in Strasbourg, “Echographic simulator” developed in cooperation with TIMC-Grenoble [43], “Knee AnteCross Ligament simulation” developed in cooperation with a surgeon at the Orthopedic Institute of Bologna, “Prototype assistance system for knee arthroscopic reconstruction” in cooperation with the Aeculap company [46]. This research axis has progressively been stopped during the period 2000-2004.

Period 5 : Geometry and Probability for motion and action.
This new period, which roughly starts at the beginning of the years 2000, represents a significative change in my research orientations. The main challenge we are addressing is to develop new models and approaches for achieving an old dream of Robotics researchers : “robots sharing the human living space”. This challenge has been first proposed in March 2002 during an European brainstorming meeting in Brussels ; this meeting has been organized during the preparation of the FET (Future Emerging Technology) call for projects “Beyond Robotics”. The research programme of my new research team (called *e-Motion* and officially created in 2004) relies on this challenge. From the scientific point of view, this challenge leads to deeply revisit the traditional approaches which are not fully adapted to the processing of uncertainty and complexity constraints coming from real world applications. Our research work is now based onto the combination of Geometric & Tological models with the Probablistic models (concept of *“Bayesian Programming”*)[1]. This approach is close to the one presented by Sebastian Thrun from Stanford University in his recent book and publications on “Probabilistic Robotics” ; it is also more and more popular in the Robotics community.

This new approach has lead us to obtain some important scientific results showing the power of Bayesian models ; these results has been published in the main conferences and journals of the domain :
− Navigation in open and dynamic environments using a combination of SLAM (Simultaneous Localization and Mapping) and Motion Planning techniques [99, 101] [86, 84, 83, 85] [68, 67, 63].
− Bayesian modeling of sensory-motor reactive behaviors for safe navigation in partly structured environments [96, 45] [109, 44].
− Concepts of *NLVO* (Non-Linear Velocity Obstacles) [105, 108, 42] and of *PVO* (Probabilistic Velocy Obstacles) [65, 66] for safe navigation in dynamic environments.
− Concept of *GHMM* (Growing Hidden Markov Model) combined with a “learn and predict” approach, for predicting the most probable future movements of various moving obstacles observed using sensors [87, 93, 82, 34, 35, 36]. A paper describing this approach is presented in 2007 at the very selective conference ISRR (International Symposium on Robotics Research) [60].

[1] see for more details the activity reports of the *e-Motion* research team at : http ://emotion.inrialpes.fr

– Concept of *BOF* (Bayesian Occupancy Filter) for robust analyzing of dynamic scenes[2] [100, 41, 39, 250, 40].

This new scientific approach has lead us to obtain important National and European research contracts, e.g. the European projects *BIBA* (Bayesian Inference and Brain Artefacts) coordinated by our team until 2005, the European project *BACS* (Bayesian Approach to Cognitive Systems) launched as a follow up of *BIBA* and coordinated by Roland Siegwart from ETHZ, and the European project *PreVent/Profusion* coordinated by Daimler Chrisler (where we are focusing on sensor fusion for Advanced Driving Assistance Systems). Our scientific results has also lead us to the signing of important R&D contracts with large companies in the field of automotive industry (e.g. TOYOTA and DENSO). All these industrial contracts are conducted in cooperation with our start-up company *Probayes*.

From the academic point of view, several workshops on these topics have successfully been organized since 2005 in the scope of the major international conferences IEEE ICRA and IEEE/RSJ IROS. These workshops about "navigation in dynamic environments" have involved several well known researchers and a significative number of participants (e.g. about 70 persons at the workshop orgnaized in Beijing in 2006). A recent book about "Autonomous navigation in dynamic environments" has been published in Springer STAR in July 2007 (C. Laugier and R. Chatila). An other book focusing on Bayesian approaches will be published very soon in Springer STAR (P. Bessiere, C. Laugier, R. Siegwart). Two special issues of the IEEE Transaction on Intelligent Transportation System and of the International Journal of Vehicle and Autonomous Systems will be soon published on these topics.

[2]Two patents based on this principle have been registered [304, 305] ; these patents are exploited in the scope of several collaboration contracts with industry (e.g. TOYOTA, DENSO, Probayes), for developing Advanced Driving Assistance Systems. The *BOF* software is integrated since 2006 in the Bayesian library *ProBT* commercialized by the *Probayes* company.

Christian Laugier **October 2007**
http ://emotion.inrialpes.fr/laugier

List of Publications

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[1] C. Laugier, R. Siegwart, A. Martinelli (Guest Editors), *Int. Jour. of Robotics Research (IJRR). Special issue on "Robots in Open and Dynamic Environments"*, Publication scheduled for Spring 2008.

[2] C. Laugier, R. Siegwart, C. Pradalier (Guest Editors), *Int. Jour. of Field Robotics (IJFR). Special issue on "Field and Service Robotics"*, Publication scheduled for Spring 2008.

[3] C. Laugier, U. Numes (Guest Editors), *IEEE Trans. on Intelligent Transportation Systems (IEEE-ITS). Special issue on "Autonomous Intelligent Vehicle : Perception and Navigation"*, Publication scheduled for September 2008.

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